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Universal Cooling of Data Centres: A CFD Analysis

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Abstract

At present, cooling of data centres efficiently is proving a challenging feat for many companies. With constantly increasing server size and IT demand, combined with the ever increasing energy consciousness of the world, many cooling systems are no longer up to the task of effectively cooling these Data Centres while maintaining an energy efficient environment. A review of journal papers, white papers, and information from companies who manufacture data centre cooling solutions was undertaken. The literature reviewed shows that any solution to this increasing problem needs to be flexible. Investigation was carried out on two different types of cooling system which showed the most promise within the literature review. An air-cooled type (hot aisle containment air cooling) and a liquid-cooled type (single-phase liquid immersion cooling) were the two types of data centre cooling systems selected. 2D simulation of each of these systems, using ANSYS© Fluent 17.2 Academic, was carried out to demonstrate the flexibility of each system when rack density is increased from 15kW to 30kW. Conclusions were drawn that air was not a flexible cooling method if changes were to be made to the IT equipment, with a maximum outlet temperature of 324K (51°C) for the 15kW system rising to 342K (69°C) when changed to a 30kW system. It was also found that liquid immersion cooling was flexible and maintained an average outlet temperature of 298K (25°C) even when the IT equipment was uprated to 30kW.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: Data Centre; Single-Phase Immersion Cooling; Hot Aisle Containment;

Nomenclature

Abbreviations

2D	Two-Dimensional

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ASIC	Application-Specific Integrated Circuit
CACS	Cold Aisle Containment System
CAD	Computer Aided Design
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handler
HACS	Hot Aisle Containment System
HVAC	Heating Ventilation and Air-Conditioning
IT	Information Technology
PPUE	Partial Power Usage Effectiveness
PUE	Power Usage Effectiveness

1. Introduction

A Data Centre is a large building that contains a group of networked computer servers, typically used by organizations to remotely store, process or distribute large amounts of data. The computer servers are typically held in racks which tend to have a capacity for around 24 single unit servers.

At present, the trends in computer technology are putting a large strain on the cost of running these data centres. There are combined concerns between ensuring the data halls are low cost and energy efficient, alongside increased demand for larger server densities and more powerful computers. This is leaving many of the most used, and trusted, methods of cooling methods for the data halls unable to meet the demands now required of them.

With the advances in technology becoming so rapid, it is often found that the cooling system designed at the beginning of a data centre build is not completely suitable for the racks and servers chosen, which are often selected near, or after, the end of the project design to ensure that the technology chosen does not end up redundant. This often results in the cooling being less effective, and can lead to hotspots and a decreased lifespan for the equipment within the data centre. Many novel technologies have been developed to try and combat the problems of higher density, energy efficiency and reduction of hot spots, but so far, there is no clear method at present that stands out as the obvious solution.

The idea behind ‘universal cooling’ (or ‘flexible cooling’) is based on two main principles (i) a flexible system which can effectively cool any size of server or rack, with minimal to no changes and (ii) that can be implemented in any part of the world. This paper looks at current cooling technologies in the hope of identifying a system that satisfies these two principles.

2. Literature Review

Emerson Network Power [1] explains the expectations on data centre design as the challenge of having to create facilities with a 20-year lifespan with technology changing every three to five years.

This statement shows the importance of developing a system that can cool a range of servers effectively, regardless of how the data centre may change and develop in the future. They also explain within their white paper that servers are replaced every three to four years on average, and the diversity of heat load requires the evaluation of ‘how to efficiently cool a Heterogeneous environment.’ Most of the literature looked at and reviewed seems to agree with the idea that flexibility within the data hall environment is important. A website for a data centre solutions provider states: ‘Data centre cooling systems must therefore be flexible and scalable, so that they can be adapted to meet changing needs’ [2] and in a whitepaper discussing the ranges and standards of cooling environments, it is stated that ‘even well managed dedicated enterprise facilities still need to have the flexibility to adapt to major additions and upgrades of IT equipment, as well as regular operational moves and changes’ [3]. The Chartered Institution of Building Services Engineer (CIBSE) [4] say that one of today’s challenges is to build sufficient flexibility to allow for ‘emerging technologies’ and ‘future growth’. Although CISBE is referring to data centre buildings as a whole, the cooling technology is a big factor when trying to ensure future flexibility. While the majority of literature agreed on the idea that cooling methods need to have a degree of flexibility to allow for future growth, TrippLite [5] does not appear to think it is possible to find one single solution that would work in all cases, and states that every installation is different, and the ideal solution depends on various governing factors.

Although a completely universal method could be considered unrealistic, a one-size-fits-most approach is plausible, and one of the key aims of this research. To find an appropriate starting point for this research, current cooling methods for data centres which offer flexibility while trying to retain low running costs and energy efficiency were analyzed. This is where the ideas presented in current literature starts to disagree, with each author presenting their own theories on what makes the most appropriate cooling solution. It is therefore necessary to evaluate all the current cooling options by looking at the arguments presented either for or against these options when it comes to cooling flexibility. A condensed version of the findings during the review is presented below.

2.1. Air based cooling

Air based cooling is the most commonly used at the present time, due to both ease of implementation and the reduced risk of server failure due to leakages when compared to liquid based methods. Sasser [6] believes air-based cooling systems with containment will continue to be the cooling system of choice in data centre environments for the near future.

2.2.1. Raised Floor Cooling

Raised floor cooling involves creating a new floor above the original and using the space between to send the cooled intake air to the servers through floor grilles in the raised floor. This can be seen in Fig. 1.

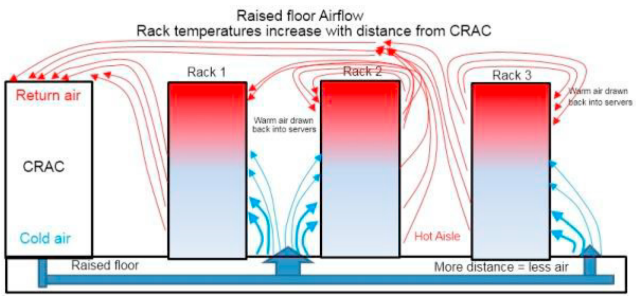

Fig. 1 - diagram of raised floor [7]

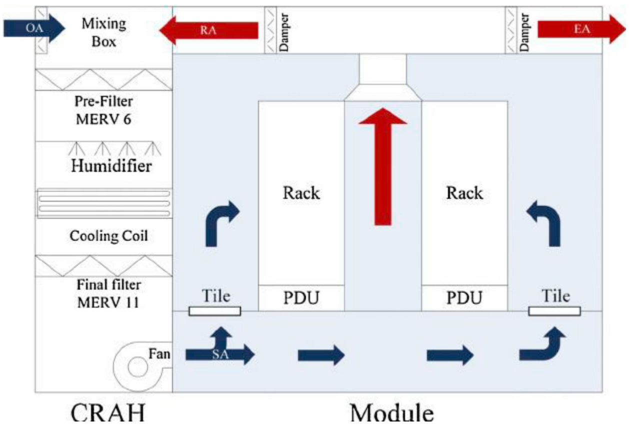

Fig. 2 – One potential layout for a Modular Data Centre [8]

This is one of the most widely used concepts in data centres today, and has been utilized for many years. Most of its flexibility benefits come from the ability to easily rearrange layouts. Pickut [9] states that 'From a layout flexibility perspective, raised floor has an advantage because perforated tiles can be easily rearranged' and Patterson and Fenwick [10] agree, saying a bonus of raised-floors is 'Flexibility for routing liquids, power, and networking under raised floor for future needs'

2.2.2. Containment

There are two different methods of containment in data centres. Hot Aisle Containment Systems (HACS) and Cold Aisle Containment Systems (CACS). Of the literature reviewed, most authors agree that hot aisle containment is the more flexible of the two. In general, most of the literature reviewed suggests that hot aisle containment has more benefits in general than the cold aisle equivalent. Sasser [6] also mentions that:

'Hot Aisle containment requires a much simpler control scheme and provides more flexible cabinet layouts than a typical Cold Aisle containment system.'

The white paper 'Hot Aisle vs. Cold Aisle Containment' by Niemann [11] agrees with this view, mentioning that one of the benefits of hot aisle containment is in fact its flexibility. He even states that: 'A HACS can be "dropped in" to the data centre without requiring any changes to the existing data centre cooling architecture'

Other Sources that agree with hot aisle containment results in the most benefits of the two containment options are Airedale [12], Neimann et al [13] and Future-Tech [14].

2.2.3. Modular Cooling

Some companies have started trying to develop a modular data centre system, where small sections can be upgraded when required. Bednar et al. [15] suggest that modular solutions can be flexible and readily deployable compared to standard data centre systems. One White paper even states that new prefabricated modular data centres can help organizations in scaling capacity at will, within weeks [16]. Nile [17] also agrees with the modular approach, saying that data centres required standardization in order to make them more reliable, and the key to flexibility in a standardized environment is modularity.

2.2.4. Free Cooling

With the recent need to improve energy efficiency, methods of free cooling have become popular research topics, however, there is not much literature on the flexibility of this type of cooling. Studies carried out by both Bulut and Aktacir [18], and Siriwardana et al. [19] examined the effects of climatic conditions in Istanbul, Turkey and parts of Australia finding that the working efficiency of free cooling is highly dependent of the climate conditions. Because of this, free cooling would not be beneficial for a fully flexible cooling environment, as it does not meet the criteria requiring the solution to be applicable to any location.

2.2. Liquid-Based Cooling

Liquid cooling has shown to have a lot of potential for flexibility; however it is often avoided due to concerns of leakage and server damage. 'The fluid may evaporate or be inert, but in all cases the risk of leaks creates a potential problem that must be weighed within the overall decision process.' [10]. New liquid cooling technologies, however, offer both flexibility and energy efficiency within high density data centre environments. Immersion cooling offers the most flexibility and comes in two forms: single phase and two phase, both of which have their benefits.

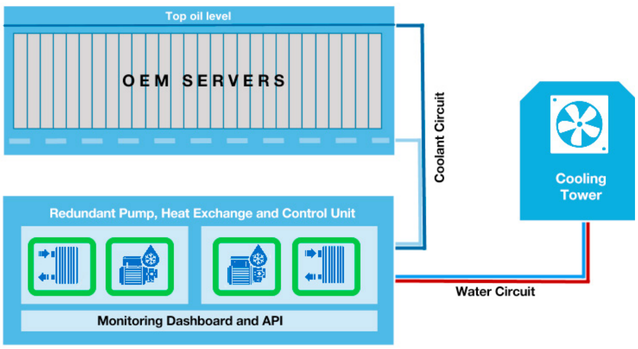

Fig. 3 - Schematic Diagram of Submer's Immersion Cooling system [20]

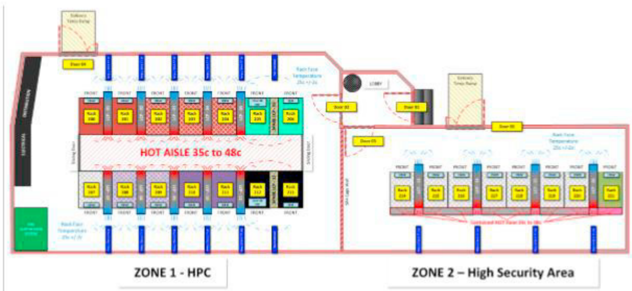

Fig. 4 - Floor plan of UK data centre (provided by MACE group)

2.2.1. Single-Phase Immersion Cooling

In single phase Immersion cooling, the cooling fluid always remains in a constant state, and is pumped through a heat exchanger to remove any heat from the servers. When compared to two-phase it offers simple design, and cheaper cooling fluid (mineral oils, vegetable-based oils etc.). In terms of a flexible environment, Submer [20] states that their solution has 'no need for extremely cold locations, is just as efficient in hot & humid climates.' This is good in terms of data centre location as it imposes no restrictions or limitations on where the user wishes to place their data centre. Submer also goes on to state that 'from standard servers to ASIC boards. You won't need special hardware.' Again, this is promising for a flexible environment [20]. Green Revolution Cooling mention, in terms of flexibility, that 'since rack capacity is a function of coolant flow, there is always the possibility of upgrading the pump module to provide more cooling overhead in the future'. [21] Therefore, it can be said that a simple change of pump is much more flexible than a full refit of an entire cooling system.

From this, single-phase immersion cooling seems to be much more flexible than current air-cooled methods.

2.2.2. Two-Phase Immersion Cooling

As with single-phase immersion cooling, two-phase immersion involves the servers being submerged in a dielectric fluid. In two-phase cooling, however, the liquid used has a very low boiling point (NovecTM, or 3MTM for example), and the heat from the servers causes it to evaporate, removing the heat from the servers. The fluid is then condensed back into a liquid state and re-introduced into the system to continue this cycle. In terms of flexibility, Allied- Control state that 'your immersion cooling enclosure will work with all your future hardware too' and later go on to mention that the technology needs to be 'assembled only once and then put to work exactly the way the customer sees fit, for many hardware generations' [22].

2.3. Summary of Findings

As it can be seen from the research conducted through this review of current literature, there are some innovative technologies that do have the 'potential' to offer a solution. In particular, 2-Phase Immersion cooling, a relatively new technology under development by Allied Control [22], stands out as having the ability to solve all the problems outlined within section one of this paper.

From these findings, the decision was initially made to compare the flexibility of 2-Phase immersion cooling to that of Air cooling with hot aisle containment, which was considered to be the most flexible method of cooling in regular use at present [6, 11]. During the simulation phase however, it was found that 2-Phase Immersion cooling was very difficult to accurately model within ANSYS© Fluent Student. Although the package offered a multi-phase simulation option, the phase change location had to be applied to the walls, and which state the fluid was in at each point had to be modelled, making it very difficult to fully and accurately model the system without a comprehensive working knowledge of both the simulation package and the cooling system. As two-phase immersion cooling is a relatively new and revolutionary cooling method for data centre cooling, detailed information that would have helped overcome this was impossible to find, and due to time limitations of the project the decision was therefore made to replace the proposed 2-phase simulations with simulations of the single-phase immersion type cooling, as it still offered great flexibility with the only change requirement being that of the pump, and literature still showed it was capable of achieving PPUE values of as low as 1.047 [23].

3. Computational Fluid Dynamics Modelling

This section will give details of the CFD models created, and also provide justification of the modelling methods used for the simulation of the two data centre rack types.

3.1. Justification for 2D Modelling

Initially the aim was to model a full data centre for each model, based on the floor plan of a UK data centre, the details of which were provided by Mace Group. The floor plan can be seen in Fig. 4.

When looking at the floor plan, the full data centre is split into two smaller data centres, and it was then decided that attention would be focused on the smaller area (zone 2). From this smaller area, it was noted that all the racks were running at the same load, and therefore it was decided that it would be possible to simply model one rack, and the result could be assumed the same for all eight racks on average. Once the decision to model one rack was made, it was realized that a 2D model would adequately illustrate the cooling for the scope of this project, as the flow would only occur in one direction through the servers. This decision was also thought to be beneficial as it meant that it would work better with the limited meshing capabilities of ANSYS© Student, and would also work better with the limited computation time availability within the university.

Although 2D modelling would not show a complete picture of everything that was happening within the data centre , it would give a very good indication of what was happening for the scope of the project, and if future work was to be undertaken upon positive results, this could then be achieved within a 3D model at a later stage as part of future research if necessary.

3.2. Computer Aided Design Model

To generate the CAD model for the 2D simulation, the integrated CAD package within ANSYS© Fluent was used, with the model settings set to 2D. For the 2D ANSYS© simulation it is the fluid that is modelled rather than the room and racks, and the appropriate boundary conditions are then set to this model in the meshing stage. An example of this model can be seen in Fig. 5 for the 15kW air-cooled simulation. The meshed model depicted in Fig. 6.

In the model shown above, the roof and floor of the data centre are the upper and lower edges of the model. The left-hand edge of the model was set as the inlet, and the right-hand edge was set as the outlet. The large open space was created to represent blanking panels and the top of the cabinet with the partition coming out to the right side from this acting as the hot aisle containment area. The remaining gaps were created to represent the servers, and when generating the simulations, it was the edges of these gaps where the heat generation was applied.

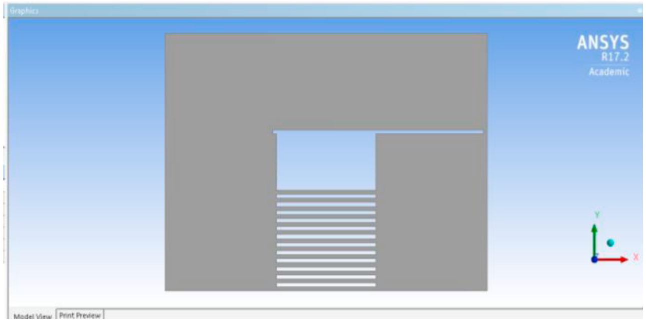

Fig. 5 - 2D CAD model for 15kW air-cooled simulation

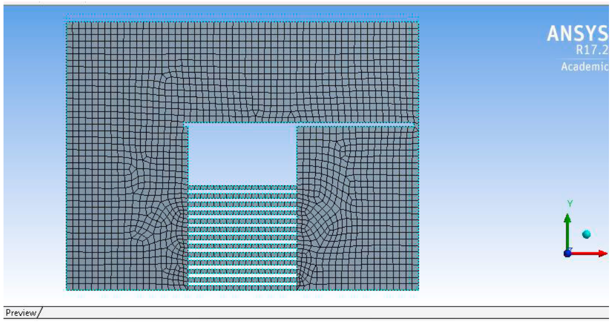

Fig. 6- 15kW air-cooled mesh (2185 elements)

3.3. Simulation

The generated results for the air-cooled models can be seen in Fig. 7. For the liquid cooled models, the simulated results can be seen in Fig.8. Each of the simulations shows the total temperature within the data centres in Kelvin within a steady state flow.

For every simulation, the inlet and exit parameters were kept constant and were set as in Table 1

Table 1. Initial boundary conditions set

Physical Quantity	Value
For the inlet, these were set as:	
Inlet Velocity	0.25m/s
Inlet Pressure:	15Pa
Inlet Temperature:	298K (25°C)
For the outlet, they were set as:	
Outlet Pressure:	15Pa
Outlet Temperature:	298K (25°C)

To set up the heat generated for each of the rack sizes, the first stage was to determine how much of the total heat was generated by each server. This was found by dividing the total heat from the rack by the number of servers in the rack and was found to be 1250W per server for the 15kW rack, and 1579W per server for the 30kW rack.

To model this in ANSYS©, it was required that the heat generated per server was provided in W/m3 so the volume of one server was calculated based on the CAD model, and the given width of the servers (as the CAD model was only 2D) which was found to be 1.3m x 0.05m x 0.8m = 0.0455m^3. The heat generated per server for each model was then divided by the volume to give a generated heat per server of 27472W/m^3 for the 15kW racks and 34702W/m^3 for the 30kW racks.

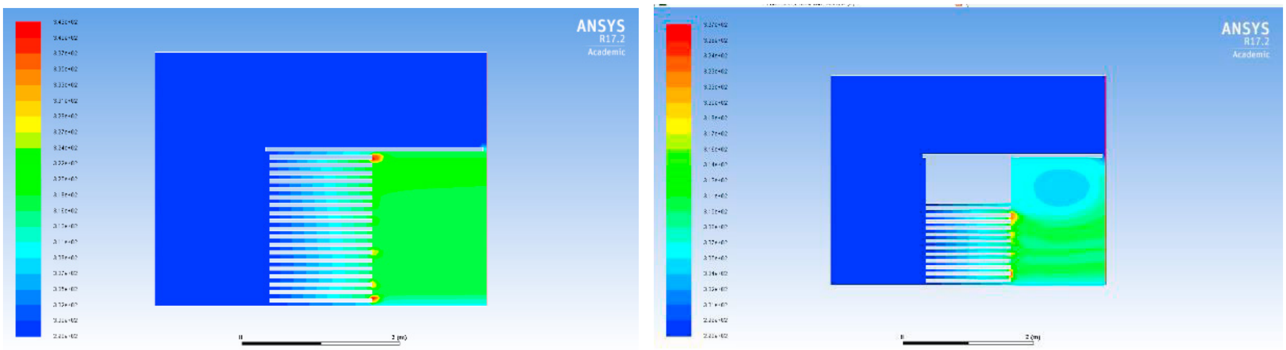

Fig. 7 - Air-cooled simulations for a) 15kW and b) 30kW

For the air-cooled racks, the cooling medium was air, which was selected with the pre-set values in ANSYS© Fluent 17.2 Academic.

For the liquid cooled racks, it was initially intended to input the parameters for the cooling fluid used by Submersify, however the data sheet did not provide the data required by ANSYS© , so the fluid used in the 2-Phase system mentioned in the literature review, Novec 3M 649, was used.

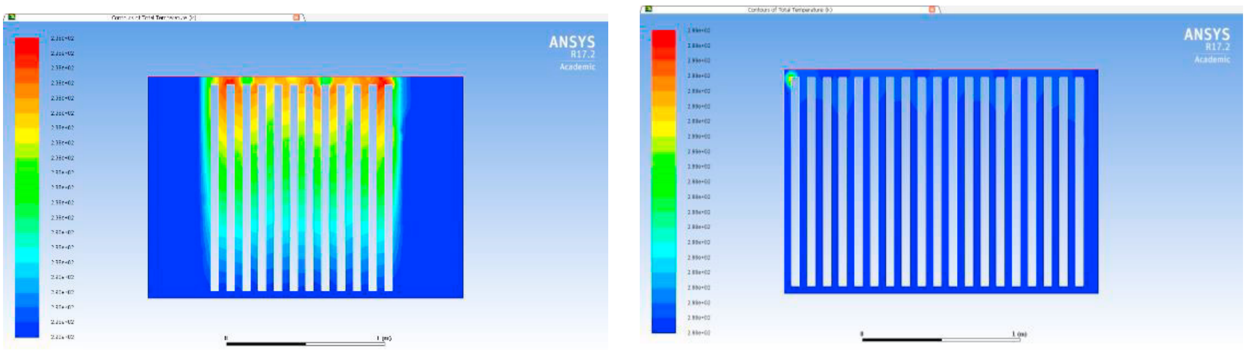

Fig. 8 - Liquid-cooled simulations for a) 15kW and b) 30kW

4. Results and Discussion

The results of the research work, in brevity, is presented below.

4.1. Air-Cooled Model

For the 15kW Air-Cooled model, the rack is cooled effectively, with the maximum air temperature leaving the racks at roughly 324K (51°C). This is only 3K or 3°C above the outlet temperatures provided for the data centre the simulations were based on (48°C). This higher value could be attributed to the simulation only allowing the air to flow around the edge of the servers and not through them as would happen in a real computer server.

For the 30kW Air-Cooled model, running on the same inlet operating conditions as its 15kW counterpart, the maximum air temperature leaving the racks is 342K (69°C). At this temperature, the likelihood of server failure during operation is high, and to rectify this, the operating conditions of the cooling system would need to be altered.

Fig. 9 shows a comparison of the temperature distribution at the rack exit for both the 15kW and 30kW models. In the graph, the temperature is measured from the back of the servers at intervals of 0.05m vertically from the floor to the roof of the rack. It can be seen from this graph that for both set ups the majority of the temperature is distributed evenly; however the 30kW rack shows a large temperature increase near the top servers of the rack, which would indicate a hotspot. This is expected from higher density racks as the heat from the lower servers rises and often the exhaust air from the lower servers is recirculated through the upper servers, decreasing the efficiency of cooling. For the 15kW rack, the temperature range from 1.2m to the top of the rack is steady and low because this is where the blanking panels are, therefore there are no servers in this area generating heat.

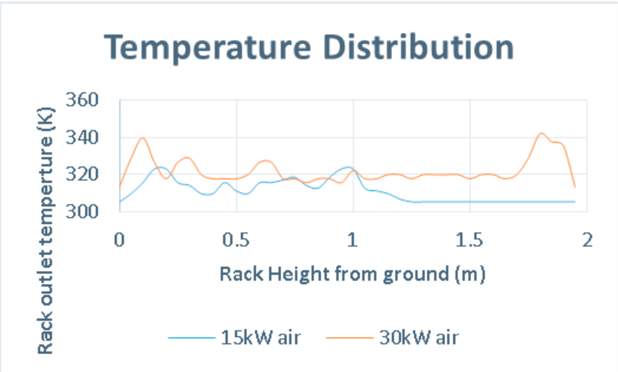

Fig. 9- Exit temperature distribution from air-cooled rack

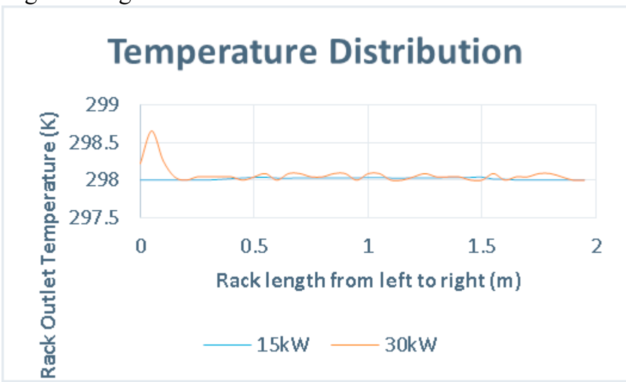

Fig. 10 - Exit temperature distribution from liquid-cooled rack

Another aspect to point out from the results of these simulations is that the air-flow remains completely unchanged as the server load is increased. While this is partly because the idea behind the project is to find a system that can effectively cool a load increase in a data centre environment with little to no change in the cooling system, it is worth noting that in reality, there would normally be a control system as part of the cooling strategy that would adjust the speed of the fans or the pressure of the system to accommodate some increases in server load. Such a system would be better demonstrated in a transient simulation which demonstrates how the server load would also naturally fluctuate throughout the working day, depending on server demand or use, and how this control strategy alters its air inlet conditions to meet these demands and minimize under- or overcooling the data centre.

From the simulations, it can be seen that the results are as would be expected for any environment where air was the main cooling fluid. The simulations show that if the server densities and heat output from these are increased then the inlet conditions also need to be changed. This is because the ability of air to actually transfer or remove heat from a source is very low when compared to liquids.

4.2. Liquid-Cooled Model

For the 15kW liquid-cooled model, the results show that the outlet and inlet temperatures are relatively stable, and the servers are kept at a temperature of around 298K (25°C) when the fluid is flowing through the rack.

This constant temperature is still maintained with the 30kW rack, showing that again, the temperature is around 298K (25°C).

Fig. 10 shows a comparison of the temperature distribution at the rack exit for both the 15kW and 30kW models. The temperature is again measured from the back of the servers at intervals of 0.05m, however due to the arrangement of the liquid cooled racks, it is now horizontally from the left hand end of the rack to the right. It can be seen from this graph that the temperature distribution is a lot more stable than that of the air-cooled racks. The 30kW rack does show a 'hot spot' on the very end server on the left, however as it is still under 299K (26°C) it is not considered an issue. It can also be seen from this graph that the temperature range does fluctuate slightly more with the 30kW rack, however it never changes more than a single degree C or Kelvin, so again would not be considered a danger to the servers' working conditions. From these simulations it could be suggested that using Novec 3M 649 as a coolant in single phase immersion cooling would be incredibly effective, and also generate a 'universal' cooling environment as this paper set out to do. However, when inputting the details of the fluid into ANSYS© , some of the values which may have been considered key values were left out, and without a full knowledge of how the system actually generates its calculations or results, it is impossible to be certain that what these results show would be true to reality. One of the main parameters that the system seemed to overlook for these simulations was that Novec 3M 649 changes phase from liquid to gas at approximately 320K (40°C) which is why it is very beneficial to 2-Phase cooling, but from these simulations it does not show how this would affect a single phase system.

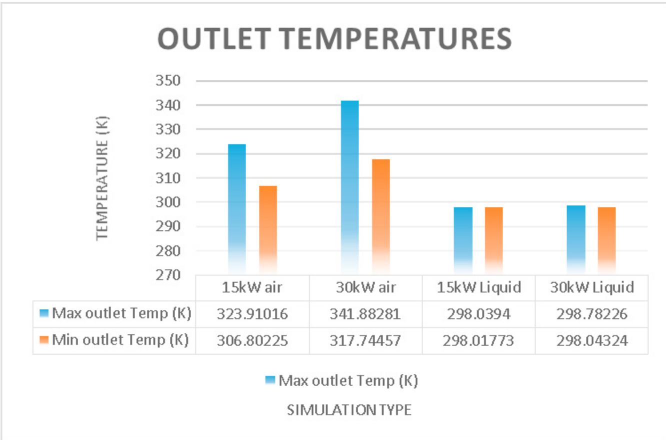

Fig. 11 - Comparison of outlet temperatures for all four simulations

4.3. Comparison

When comparing the flexibility of cooling of the air and liquid cooled simulations, it can be noted that liquid cooling meets the requirements of a 'universal' cooling system as set out by the project, whereas air cooling does not. It can also be seen from Fig. 11 that the outlet temperatures for both air-cooled models is much greater than those of the liquid cooled counterparts.

5. Conclusions and Future Work

The study of current data centre cooling methods leads to the following conclusions.

a. When using air as the cooling medium for electronics cooling, any changes to IT equipment that cause a larger heat generation will also require changes to the cooling system operating conditions. From this it can be concluded that although air has been an effective form of cooling data centres, it cannot be considered flexible or universal under the terms outlined by this paper.
b. Alternatively, when using a liquid immersion type of cooling system, changes to the IT loading did not appear to affect the ability of the chosen fluid, Novec 3M 649, to effectively cool the IT equipment. The results shown suggest that it is possible to have a data centre cooling environment that is flexible and can meet demands for the constantly changing IT requirements of the modern world, although more would need to be done to verify these results as accurate or plausible.

Future work on this research would be recommended as follows.

i. 3D simulation of both the systems, for a full data centre model, and using the appropriate CFD software package suitable for data centre modelling. A transient version of these simulations would also be beneficial as the current simulations are just steady state, and in reality, the loading on data centre IT equipment will fluctuate throughout the day, depending on the data demands. In depth energy analysis, looking into the actual energy use of running each system so that comparisons on actual energy use can be shown.

ii. Costing analysis, to look into the cost of implementing both systems, alongside the cost of running both systems over a certain time period. The analysis would preferably include the cost of any changes or upgrades to the cooling system if server size is increased at a later date, and the analysis would help show any financial benefits of one system over another.

Acknowledgements

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